

Locating the γ -ray Flaring Emission of Blazar AO 0235+164 in the Jet at Parsec Scales Through Multi Spectral Range Monitoring

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We present observations of a major outburst at centimeter, millimeter, optical, X-ray, and γ -ray wavelengths of the BL Lacertae object AO 0235+164 in 2008. Here we reproduce the results of the analysis of these observations, already presented in Agudo et al. [2011b]. We analyze the timing of multi-waveband variations in the flux and linear polarization, as well as changes in Very Long Baseline Array (VLBA) images at 7 mm with ~ 0.15 milliarcsecond resolution. The association of the events at different wavebands is confirmed at high statistical significance by probability arguments and Monte-Carlo simulations. A series of sharp peaks in optical linear polarization, as well as a pronounced maximum in the 7 mm polarization of a superluminal jet knot, indicate rapid fluctuations in the degree of ordering of the magnetic field. These results lead us to conclude that the outburst occurred in the jet both in the quasi-stationary core and in the superluminal knot, both at > 12 parsecs downstream of the supermassive black hole. We interpret the outburst as a consequence of the propagation of a disturbance, elongated along the line of sight by light-travel time delays, that passes through a standing recollimation shock in the core and propagates down the jet to create the superluminal knot. The multi-wavelength light curves vary together on long time-scales (months/years), but the correspondence is poorer on shorter time-scales. This, as well as the variability of the polarization and the dual location of the outburst, agrees with the expectations of a multi-zone emission model in which turbulence plays a major role in modulating the synchrotron and inverse Compton fluxes.

1. Introduction

Our understanding of the processes leading to the generation of γ -ray emission from blazars, the most extreme active galactic nuclei, depends on where those γ -rays originate. This is currently the subject of considerable debate [e.g., Agudo et al. 2011a, Marscher & Jorstad 2010, Tavecchio et al. 2010]. Two main locations of the site of γ -ray emission in blazars have been proposed. The first is close ($\lesssim 0.1$ – 1 pc) to the supermassive black hole (BH). The second one, a region much farther ($\gg 1$ pc) from the BH, is beyond the “core” where the jet starts to be visible at millimeter wavelengths with VLBI. Supporting this second scenario, Agudo et al. [2011a] unambiguously locate the region of γ -ray flares > 14 pc from the BH in the jet of OJ287 through correlation of millimeter-wave with γ -ray light curves and direct ultrahigh-resolution 7 mm imaging with the VLBA. Similar results are obtained by Marscher et al. [2010] and Jorstad et al. [2010] for PKS 1510–089 and

3C 454.3, respectively.

In Agudo et al. [2011b] we investigate the location and properties of a radio to γ -ray outburst in the BL Lacertae object AO 0235+164 (0235+164 hereafter, $z = 0.94$), which results are reproduced here.

2. Observations

Our photo-polarimetric monitoring observations of 0235+164 (Figs. 1-3) include (1) 7 mm images with the VLBA from the Boston University monthly blazar-monitoring program, (2) 3 mm observations with the IRAM 30m Telescope, and (3) optical measurements from the following telescopes: Calar Alto (2.2m Telescope, observations under the MAPCAT program), Steward Observatory (2.3 and 1.54m Telescopes), Lowell Observatory (1.83m Perkins Telescope), San Pedro Mártir Observatory (0.84m Telescope), Crimean Astrophysical Observatory (0.7m Telescope), and St. Petersburg State University (0.4m

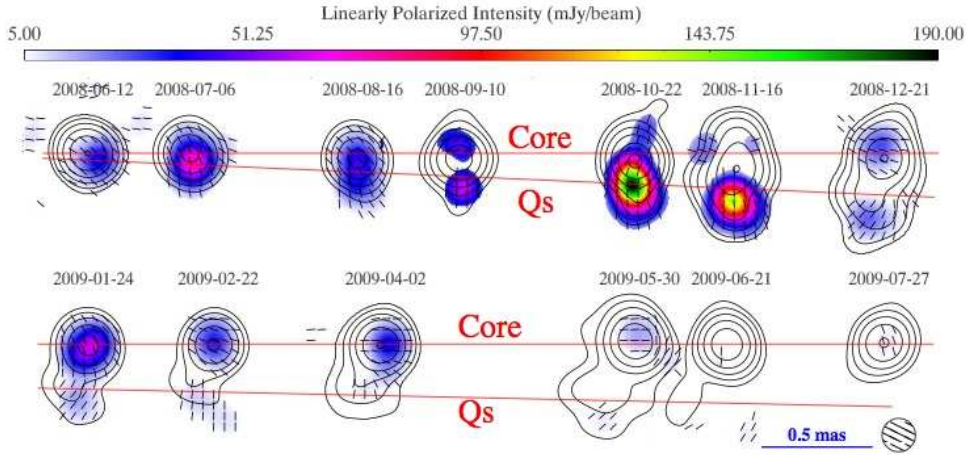


Figure 1: Sequence of 7 mm VLBA images of 0235+164 convolved with a FWHM = 0.15 mas circular Gaussian beam. Contour levels represent total intensity (levels in factors of 2 from 0.4 to 51.2% plus 90.0% of peak = 4.93 Jy/beam), color scale indicates polarized intensity, and superimposed sticks show the orientation of χ . Reproduced from Agudo et al. [2011b].

Telescope). Our total flux light curves (Fig. 2) include data from the *Fermi*-LAT γ -ray (0.1–200 GeV) and *Swift*-XRT X-ray (2.4–10 keV) observatories, available from the archives of these missions, and RXTE at 2.4–10 keV. Optical *R*-band fluxes come from the Tuorla Blazar Monitoring Program, the Yale University SMARTS program, and Maria Mitchell and Abastumani Observatories. Longer wavelength light-curves were acquired from the Submillimeter Array (SMA) at 850 μ m and 1 mm, the IRAM 30m Telescope at 1 mm, the Metsähovi 14m Telescope at 8 mm, and both the Owens Valley Radio Observatory (OVRO) 40m Telescope *Fermi* Blazar Monitoring Program and University of Michigan Radio Astronomy Observatory (UMRAO) 26m Telescope at 2 cm.

We followed data reduction procedures described in previous studies: VLBA: Jorstad et al. [2005]; optical polarimetric data: Jorstad et al. [2010]; IRAM data: Agudo et al. [2006, 2010]; SMA: Gurwell et al. [2007]; Metsähovi: Teräsranta et al. [1998]; OVRO: Richards et al. [2011]; UMRAO: Aller et al. [1985]; *Swift*: Jorstad et al. [2010]; *RXTE*: Marscher et al. [2010]; and *Fermi*-LAT: Agudo et al. [2011a], Marscher et al. [2010]. See Agudo et al. [2011b] for further details about the X-ray and γ -ray data reduction.

3. Major Millimeter Flare in 2008 Related to a New Superluminal Knot

We model the brightness distribution of the source at 7 mm with a small number of circular Gaussian components (Fig. 1). Our model fits include a bright superluminal feature (Qs, the brightest jet feature

ever detected in this object) propagating from the core at $\langle \beta_{app} \rangle = (12.6 \pm 1.2) c$.

The ejection of Qs was coincident with the core near the start of an extreme mm outburst (08_{mm} in Fig. 2)). Figure 2 shows that radio and mm outbursts in 2008 (08_{rad} and 08_{mm}) contain contributions from both the core and Qs. Their contemporaneous co-evolution suggests that the disturbance responsible for the ejection of Qs extended from the location of the core to Qs in the frame of the observer, which could have resulted from light-travel delays [e.g., Agudo et al. 2001, Gómez et al. 1997, Mimica et al. 2009]. The rarity of the 08_{rad}, 08_{mm}, and Qs events strongly implies that they are physically related.

The jet half-opening-angle of 0235+164 [$\alpha_{int}/2 \lesssim 1^\circ 25'$, see Agudo et al. 2011b] and the average FWHM of the core measured from our 31 VLBA observing epochs in [2007,2010] ($\langle \text{FWHM}_{core} \rangle = (0.054 \pm 0.018) \text{ mas}$), constrain the 7 mm core to be at $d_{core} = 1.8 \langle \text{FWHM}_{core} \rangle / \tan \alpha_{int} \gtrsim 12 \text{ pc}$ from the vertex of the jet cone.

4. Contemporaneous Flares from γ -ray to Radio Wavelengths

Figure 2 reveals that the 08_{rad} and 08_{mm} flares were accompanied by sharp optical, X-ray, and γ -ray counterparts (08_{opt}, 08_X, and 08 _{γ} flares, respectively). Our formal light-curve correlation analysis (Fig. 4) –performed following Agudo et al. [2011a]– confirms the association of γ -ray variability with that at 2 cm, 8 mm, 1 mm, and optical wavelengths at $> 99.7\%$ confidence. The flux evolution of the VLBI core is also correlated with the γ -ray light curve at $> 99.7\%$ con-

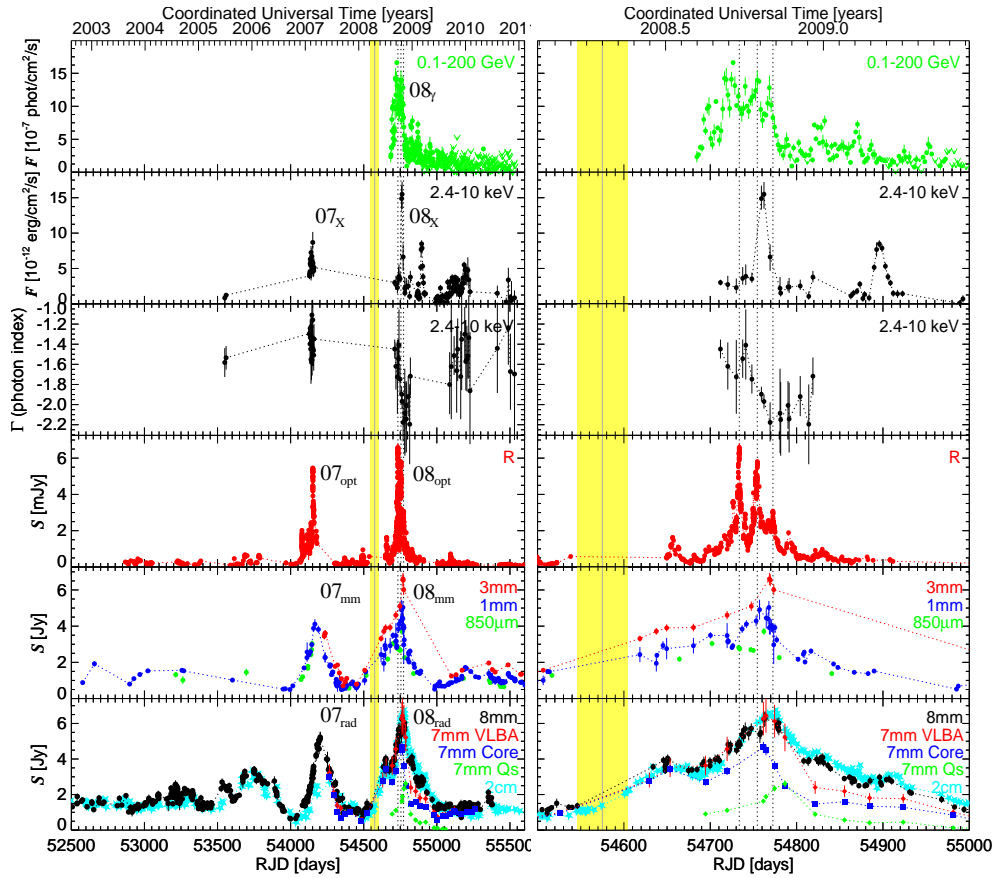


Figure 2: *Left*: Light curves of 0235+164 from γ -ray to millimeter wavelengths. X-ray photon index evolution from the *Swift*-XRT data is also plotted. Vertical dotted lines mark the three most prominent 08_{opt} optical peaks. The yellow area represents the time of ejection of feature Qs within its uncertainty. RJD = Julian Date – 2400000.0. *Right*: Same as left panel for RJD \in [54500, 55000]. Reproduced from Agudo et al. [2011b].

fidence. Moreover, the evolution of the degree of optical linear polarization (p_{opt}) and X-ray light curve are also correlated with the optical R -band, 1 mm, and 2 cm light curves at $> 99.7\%$ confidence (Fig. 5), further indicating that the extreme flaring activity revealed by our light curves is physically related at all wavebands from radio to γ -rays.

There is, however, no common pattern to the discrete correlation function (DCF) at all spectral ranges. This implies that, although there is correlation on long time-scales (years), on short time-scales ($\lesssim 2$ months) the variability pattern does not correspond as closely. This is the result of the intrinsic variability pattern rather than the irregular time sampling at some spectral ranges.

5. Correlated Variability of Linear Polarization

Figure 3 reveals extremely high, variable optical polarization, $p_{\text{opt}} \gtrsim 30\%$, during the sharp 08_{opt} optical peaks. Whereas the integrated millimeter-wave

degree of linear polarization (p_{mm}) and that of the 7 mm core remain at moderate levels $\lesssim 5\%$, the polarization of Qs ($p_{\text{mm,Qs}}$) peaks at the high value of $\sim 16\%$ close to the time of the second sharp optical sub-flare. The coincidence of this sharp maximum of $p_{\text{mm,Qs}}$ in the brightest superluminal feature ever detected in 0235+164 with the (1) high optical flux and polarization, (2) flares across the other spectral regimes, and (3) flare in the 7-mm VLBI core, implies that the ejection and propagation of Qs in 0235+164's jet is physically tied to the total flux and polarization variations from radio to γ -rays.

On long time-scales (years), the linear polarization angle at both optical (χ_{opt}) and millimeter (χ_{mm} and $\chi_{\text{mm}}^{\text{core}}$) wavelengths varies wildly, without a preferred orientation or systematic common trend. However, during flare 08_{opt}, χ_{opt} maintains a stable orientation at $(100 \pm 20)^\circ$, whereas $\chi_{\text{mm}}^{\text{Qs}}$ is roughly perpendicular to this ($\sim 0^\circ$), as expected for a plane-perpendicular shock wave propagating to the south towards Qs. Owing to the large peak value of Qs, $p_{\text{mm,Qs}}^{\text{max}} \sim 16\%$, one cannot explain the orthogonal optical-millimeter polarizations by opacity effects. Instead, we propose

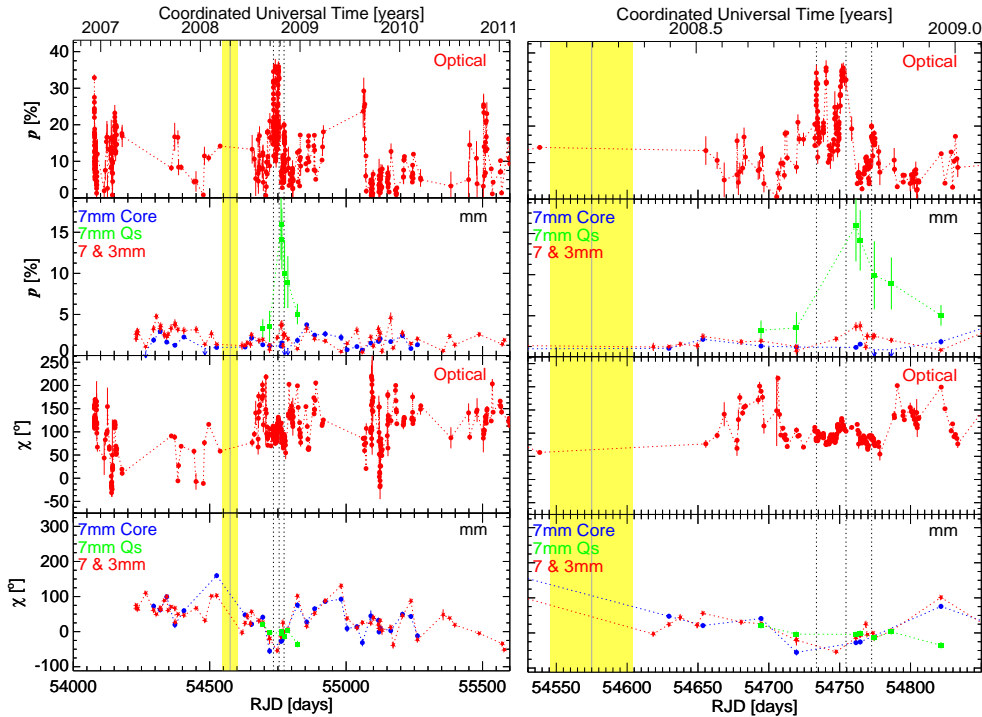


Figure 3: *Left*: Long term optical and millimeter-wave linear polarization evolution of 0235+164 in the RJD=[54000,55600] range. *Right*: Same as left panel for RJD ∈ [54530, 54850]. Reproduced from Agudo et al. [2011b].

that the optical polarization mainly arises in a conical shock associated with the 7-mm core, while the millimeter-wave polarization results from a propagating shock front associated with Qs. We surmise that the moving shock also emits polarized optical radiation, since the optical polarization drops precipitously when the orthogonal polarization of Qs peaks (Fig. 3-right).

6. Low Probability of Chance Coincidences

The relationship among the γ -ray, optical, and radio-millimeter flares is supported by probability arguments. If the flares occur randomly, the probability of observing, at any time, a γ -ray outburst like the one reported here (i.e., with flux $\gtrsim 10^{-6}$ phot cm $^{-2}$ s $^{-1}$ and duration ~ 70 days) is $p_\gamma = 0.08$. For optical and radio-millimeter wavelengths, this probability is $p_{\text{opt}} = 0.04$ and $p_{\text{mm}} = 0.15$, respectively. Thus, if the flares at different wavelengths were random and independent of each other, the probability of observing a γ -ray, optical, and radio-millimeter flare at any given time is $p_{\gamma,\text{opt},\text{mm}} = 5 \times 10^{-4}$. This counters the null hypothesis of random coincidence at 99.95% confidence.

7. Observational Evidences

The coincidence of the ejection and propagation of Qs –by far the brightest non-core feature ever reported in 0235+164– with the prominent γ -ray to radio outbursts and the extremely high values of p_{opt} and $p_{\text{mm,Qs}}$ provides convincing evidence that all these events are physically connected. This is supported by probability arguments and by our formal DCF analysis, which unambiguously confirms the relation of the γ -ray outburst in late 2008 with those in the optical, millimeter-wave (including the 7-mm VLBI core) and radio regimes. We locate the millimeter core at $d_{\text{core}} \gtrsim 12$ pc from the vertex of the jet.

8. Conclusions

We identify the 7-mm core as the first re-collimation shock near the end of the jet's acceleration and collimation zone [ACZ Jorstad et al. 2007, Marscher et al. 2008, 2010]. Superluminal feature Qs is consistent with a moving shock oriented transverse to the jet axis, given the extremely high $p_{\text{mm,Qs}}$, with $\chi_{\text{mm}}^{\text{Qs}}$ parallel to the direction of propagation of Qs. The flux evolution of the core appears closely tied to that of Qs, and its light curve is correlated at high confidence with those at γ -ray, optical, and millimeter wavelengths. This suggests that Qs is the head of an extended disturbance, perhaps containing a front-back structure

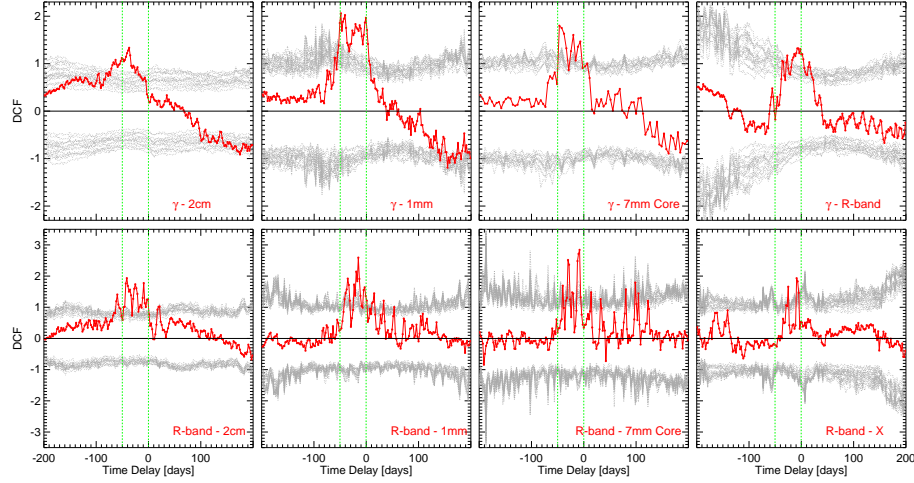


Figure 4: Grid of DCF of labeled light-curve pairs during the maximum time period RJD = [52200, 55600]. *Top* row of panels show DCF with γ -ray light-curve, whereas *bottom* row show DCF with R -band light-curve. Grey dotted curves at positive (negative) DCF values symbolize 99.7 % confidence limits for correlation against the null hypothesis of stochastic variability. Green dashed lines at 0 and -50 day time-lags are drawn for reference. Reproduced from Agudo et al. [2011b].

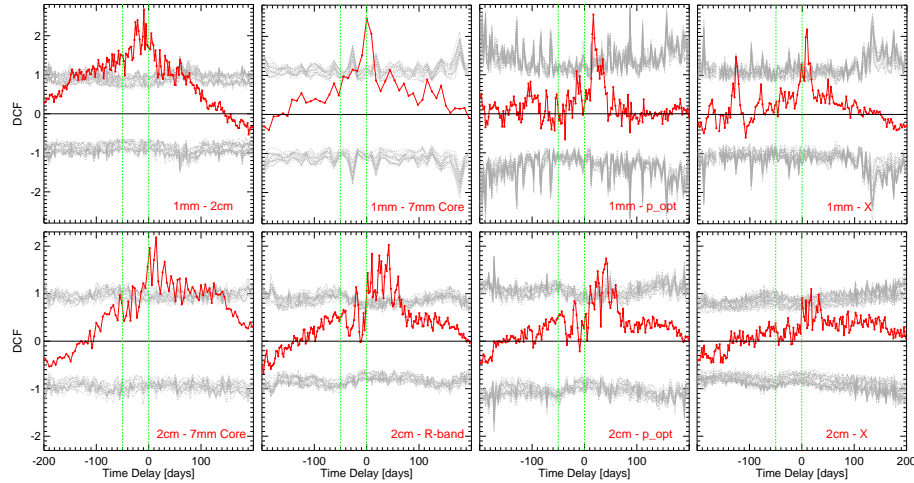


Figure 5: Same as Fig. 4 but for the 1 mm light-curve (*top*) and the 2 cm light-curve (*bottom*). Reproduced from Agudo et al. [2011b].

stretched by light-travel delays in the observer's frame [see, e.g., Aloy et al. 2003].

Under this scenario, the radio/millimeter-wave and optical (and perhaps X-ray) synchrotron flares start when the front region crosses the conical shock at the core, where the jet is at least partially optically thin (Fig. 6). This interaction accelerates electrons, and produces inverse Compton γ -ray emission from the up-scattering of IR-optical photons. When the back region of the moving perturbation encounters the core, their interaction again produces efficient particle acceleration, which is seen as a sudden optical and radio/millimeter synchrotron emission enhancement. The subsequent optical variability is produced by the passage of the remaining shocked turbulent

plasma in the back structure through the core. During the different optical sub-flares, the integrated radio/millimeter synchrotron flux keeps rising. This radio/millimeter outburst is more prolonged owing to the longer synchrotron cooling-time of electrons radiating at these wavelengths and the lower speed of the back structure. Indeed, Qs does not reach its maximum radio/millimeter-wave flux until traveling a projected distance of ~ 0.13 mas from the core. When the entire front-back structure passes across the core, the synchrotron emission declines rapidly at optical (and, if relevant, X-ray) frequencies, as does the γ -ray emission. The decay of the radio/millimeter-wave emission is more gradual (see above).

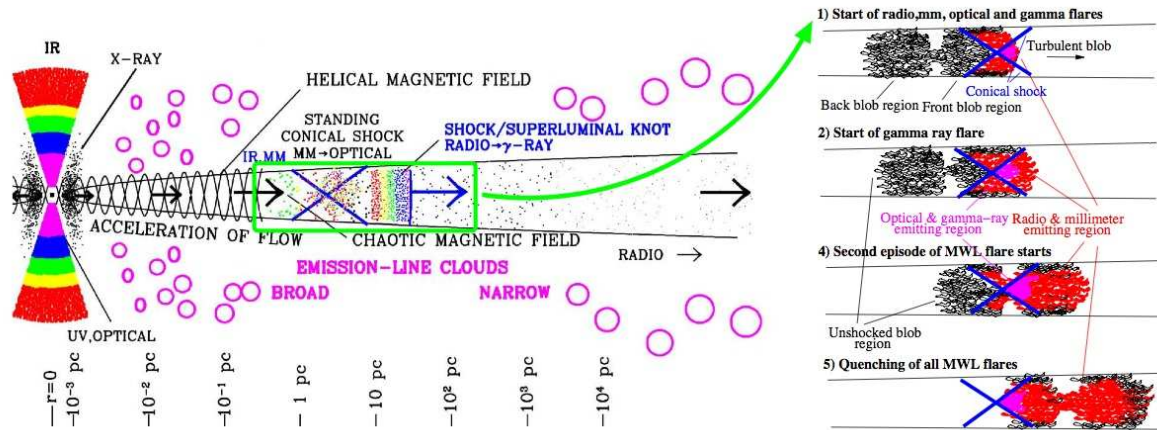


Figure 6: Scheme of proposed model for the multi-wavelength flaring behavior of AO 0235+164. Radio-loud AGN sketch adapted from Marscher [2006].

Acknowledgments

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